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APPLICATION OF CONTINUUM DAMAGE MECHANICS FOR IN-SERVICE REAL FATIGUE CRACKING SCENARIOS

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Abstract: Fatigue and Damage Tolerance (F&DT) evaluation for aeronautical structures is a complex process able to produce robust designs and ensure high safety standards. Nevertheless, fatigue cracking events are still happening in any aircraft fleet, in most of the cases due to an interaction of several causes that cannot be properly combined in the standard F&DT evaluations.
The evaluation and correlation of in-service findings is essential to ensure that root cause is identified and adequate corrective actions are taken. However this is not an easy task as these events are usually associated with complex structural and material behaviors that are difficult to be properly predicted under certain conditions by current F&DT certification methods.

This paper presents an Airbus real practical application in the context of an in-service cracking scenario using more sophisticated state-of-the-art F&DT prediction methods techniques combining a high fidelity Modelling & Simulation capability with a fatigue damage model based on the Continuum Damage Mechanics framework.

Details of the overall process followed as a result of an in service crack finding will be provided. This process includes a full damage correlation against a specific subcomponent test and in-service experience as part of the Continuous Airworthiness verification, validation and acceptance criteria.

Keywords: In-service, Continuous Airworthiness, Simulation, CDM

INTRODUCTION

The Fatigue and Damage Tolerance evaluation of an airframe structure is one of the means to show compliance with the current aeronautical regulations requiring that catastrophic failure due to fatigue, manufacturing defects, environmental effects or accidental damages will be avoided throughout the operational life of the airplane.

Despite all the efforts employed during the fatigue and damage tolerance evaluation at the entry into service of an aircraft, which is mainly based on past experience, physical tests and detailed analysis supported by extensive subcomponent fatigue tests, the fatigue in service cracking events continue being one of the main fleet maintenance issues. Such situations have also to be properly addressed in order to keep the minimum level of safety required in the current aeronautical regulations to maintain the aircraft airworthy as part of the continued airworthiness regulations.

Within this context, the capability to refine the classical fatigue and damage tolerance evaluation to be able to predict and evaluate more complex structural and material behavior in order to ensure that root cause is identified and adequate corrective actions are taken is more than essential for Airbus as part of the aircraft industry.

This paper, presents two real cases from the aircraft in service experience, with in service cracking scenarios on quite complex structural details, where the contribution of several factors to the crack initiation and subsequent propagation makes quite difficult, for the traditional approach based on deterministic fatigue and damage tolerance analysis, to have a reliable prediction. In order to be able to cope with such situations, Airbus has developed the capability to apply more sophisticated techniques in terms of fatigue, crack propagation and residual strength prediction methods, such the one based on very detailed finite element simulations combined with a fatigue damage accumulation model based on Continuum Damage Mechanics (CDM) framework, object of the present paper.

The CDM concept, although is not new since the first developments are found in the literature from 1958, has not been widely applied in the aeronautical industry mainly due to the high simulation capabilities needed and due to the lack of validation and verification experience on real applications, key aspects playing an important role in the practical side for every industrial application but also on the high reliability needed in particular for the aeronautical industry.

One of the relevant key aspect for the aeronautical industry when exploiting the CDM advanced simulation to predict crack initiation and propagation on complex structural scenarios, such the ones presented in this paper, is the capability of analyzing the fatigue initiation process and the crack propagation mechanism in one single step, by removing the classical distinction between the initiation and propagation mechanisms inherent to the classical theories.

Within the next chapter of the paper, a brief introduction to the CDM model general concepts and the proposed damage model selected for the two applications is described.

Previous experiences in Airbus of advanced simulations applied for F&DT applications can be found in [1][2][3]. As explained above, in this paper, two additional ones will be presented, one dealing with a crack in a metallic fuselage frame attachment to a composite skin and a second one dealing with a crack in the metallic upper skin of a horizontal tail plane.

To conclude, a summary of the results obtained through such advanced simulations are explained, the relevant lessons learnt from the mentioned applications are proposed, including recommendations about the validation and verification processes to assure a certain level of control of the uncertainties.

CONTINUUM DAMAGE MECHANICS

Introduction to CDM

Conventional methods used in F&DT evaluation are usually based on the experimental derivation of a set of material curves which relates the stress (or strain) loading at which the material is subjected to the fatigue cracking nucleation and propagation behavior of the material. This conventional approach can be of limited application for complex cases involving such as the evaluation of in-service fatigue findings.

An alternative approach based on damage mechanics has been applied in this paper. Kachanov first introduced the concept of damage mechanics in 1958 to predict creep failure of metals. In 1978, Lemaitre and Chaboche, developed the concepts of material damage and established a new branch of mechanics by means of the theory of continuum mechanics. This theory was called Continuum Damage Mechanics (CDM). This field has developed significantly in the last decades to model different modes of failure in materials such as ductile damage, fatigue in metals or composites failure. Further details about CDM can be found in [4][5].

Representative Volume Element (RVE) and Damage Variable

CDM describes the development of cracks, voids or cavities in each scale that lead to deterioration of the mechanical properties of the materials. This method is a phenomenological approach, which treats a damaged material element with certain properties as if it were in a homogeneous medium regardless to how those properties physically are affected by damage by means of the concept of the Representative Volume Element (RVE). Through the RVE, a material with discontinuous microstructure can be idealized as a continuum by means of the statistical average of the mechanical state in the material.

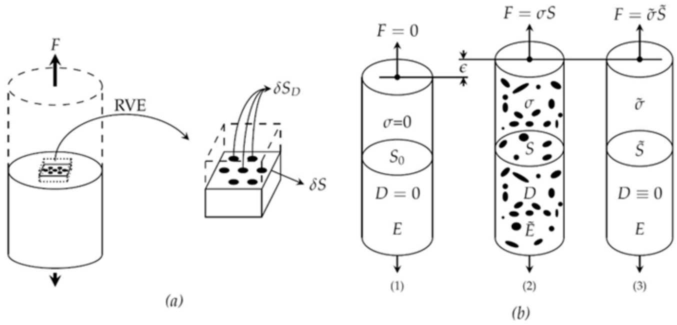

Figure 1: Representative Volume Element concept

In CDM, a damage variable is defined to represent the average material degradation within the RVE. The most general tensorial damage variable is expressed in tensorial form, however, application of this damage tensor in a damage model is difficult in practical situations and consequently a scalar damage variable is usually considered.

An important concept in CDM is the effective stress, it represents the increase of stress σ induced by the external loading F due to decrease in the load-carrying area. The effective stress is defined as:

$$\tilde{\sigma}_{ij} = \frac{\sigma_{ij}}{1 - D}$$

The damage variable can be also described as a function of the effective elastic modulus written as follows:

$$D = 1 - \frac{\tilde{E}}{E}$$

where Ẽ is the elastic modulus of the damaged material, which varies linearly with the damage variable D.

CDM application for fatigue cracking evaluation

As previously described, CDM relies on the definition of a damage variable to represent macroscopically the effect of micro-scale damages on the material. This approach can be applied to characterize fatigue cracking in metallic materials by using dedicated damage models able to establish the relation between the applied cyclic loading and the evolution of the damage variable.

A significant number of CDM fatigue models have been developed in the last decades. These damage models propose a nonlinear damage law, which can be based on stresses or strains, depending on the model. The nonlinear law determines the rate of accumulation of damage as a function of the applied loading cycles in contrast with classical Miner's rule, which establishes a linear law.

For the applications described in this paper, a fatigue damage model based on alternating strains, proposed by Peerlings in [6], has been considered. The damage equation is established as:

$$D = -\frac{1}{\alpha}\ln\left(1 - \frac{2\alpha C}{\beta+1}\,\varepsilon_{\mathrm{a}}^{\beta+1} N\right)$$

Where:

- εa is the amplitude of the strain cycle associated to the applied load cycle
- N is the number of applied cycles
- α, β and C are material-specific parameters

The damage evolution law can be integrated condition between D=0 to D=1 to compute the total fatigue life in a uniaxial loading condition:

$$N_F = \frac{\beta+1}{2\,\alpha\,C}\,(1 - e^{-\alpha})\,\varepsilon_a{}^{-(\beta+1)}$$

CDM application for residual strength evaluation

The Residual Strength evaluation consists on the determination of the remaining load-carrying capability of a damaged or cracked structure up to the static failure. The material failure can be modelled using a ductile damage model in the simulation. The selected ductile damage model is based on the equivalent strain to failure as a function of stress triaxiality ([7][8]).

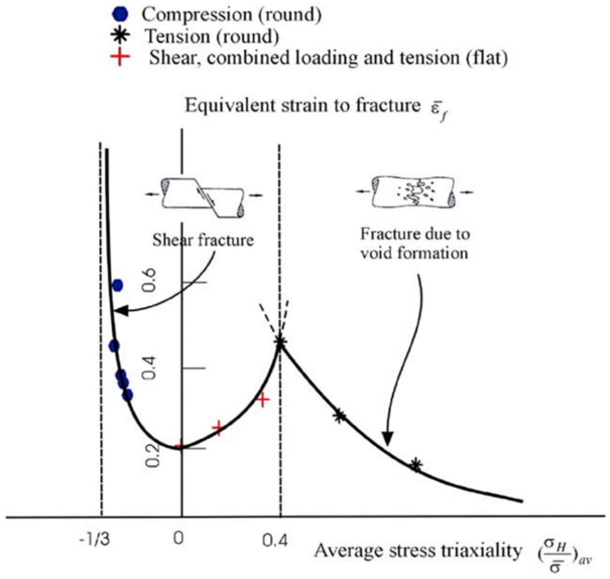

Figure 2: Equivalent strain to fracture - triaxiality ([8])

Stress triaxiality is defined as the ratio of hydrostatic pressure to the von Mises equivalent stress. The triaxiality of the stress state is known to influence the amount of plastic strain, which a material experiences before ductile failure occurs. As it can be seen in the previous figure, different fracture mechanisms are considered, this curve has been obtained experimentally and is based on shear fracture mechanism, the void growth and the combination of shear decohesion and void growth.

The relation between equivalent fracture strain and stress triaxiality for the corresponding material of the structure can be obtained by dedicated coupon tests or by the adjustment of existing analytic or empirical formulations for similar materials to match the actual behavior of the material in terms of structural strength based on known design allowable such as the ultimate tensile stress and the ultimate bearing allowable.

CDM NUMERICAL IMPLEMENTATION

Simulation framework

The Continuum Damage Mechanics methodology described in the previous chapter was numerically implemented in a Finite Element Method framework using as baseline software SIMULIA Abaqus [12]. This software is selected due to its nonlinear capabilities and extensive experience, verification and validation within Airbus.

Numerical implementation for fatigue cracking evaluation

For fatigue cracking evaluation, the numerical implementation scheme is summarized in the table below:

Table 1: Numerical implementation for fatigue cracking.

FE Method	*Implicit FEM*
FE Solver	*Abaqus Standard 2016*
CDM implementation	*Abaqus User's Subroutines*

To properly implement the damage model, the material elastic plastic model included in the simulation has to be able to account for the progressive degradation of the material elastic modulus to the accumulation of damage.

As a baseline constitutive material behavior, an isotropic elasto-plasticity model is considered. To include the effect of damage accumulation, the elastic modulus of the material is replaced by the effective elastic modulus as detailed in the previous chapter. The implementation of the damage variable in the FE model is done using a Field Variable controlled by a User's Subroutine, which includes the CDM damage law. This variable represents the damage scalar variable and is modifying the elastic modulus of the material to model its degradation.

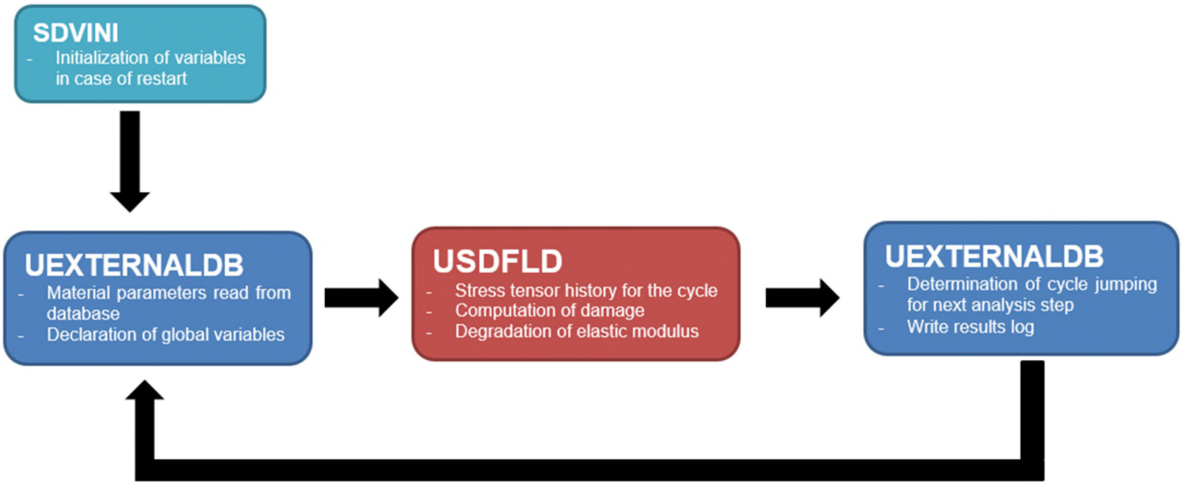

Figure 3: Subroutine implementation scheme for CDM fatigue cracking

Numerical implementation for residual strength evaluation

Residual strength failure is evaluated as a quasi-static phenomenon however, its numerical simulation requires the capability to model the sudden failure of the structure, which implies sudden changes in the model stiffness.

For metallic structures, conventional structural simulations based on the Implicit Finite Element Method present significant difficulties to properly capture this kind of phenomena, as it is required to obtain a converged solution at each time step of the simulation. The process to achieve convergence in the solution can require a very large number of iterations with very small time steps, which can result in impractical computational costs.

This limitation in the simulation of residual strength failures can be overcome by using the Explicit Finite Element Method. Explicit Simulations are conceived for highly dynamic phenomena, however quasi-static failures can be simulated by ensuring that kinetic energy remains negligible (appropriate definition of analysis times and mass scaling).

For residual strength evaluation, the numerical implementation scheme is summarized in the table below:

Table 2: Numerical implementation for residual strength evaluation.

FE Method	Explicit FEM
FE Solver	Abaqus Explicit 2016
CDM implementation	Abaqus Ductile Damage

APPLICATION #1: CRACK FINDING IN FUSELAGE FRAME FOOT

CDM process implementation for unfolding use case

In aeronautical structures, joints subjected to unfolding loads are complex areas to evaluate the fatigue and damage tolerance structural capabilities. Conventional methodology based on semi empirical analytical approaches is not able to accurately predict the crack initiation, propagation and residual strength behavior due to the nature of the stress distribution, crack nucleation and load redistribution.

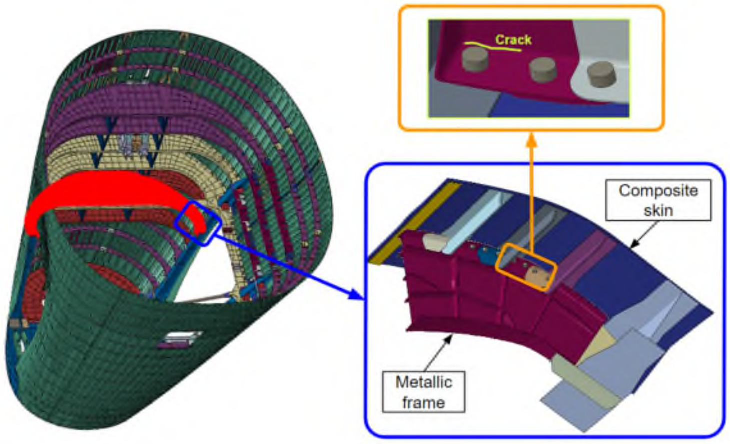

Figure 4: Fuselage frame to skin joint subjected to unfolding loads and associated crack

Continuous Damage Mechanics simulation capabilities has been used to predict the real response of a fuselage metallic frame to the skin joint of a commercial aircraft. The objective is both to predict the fleet response for crack initiation and propagation, and the residual strength capabilities. The application of this innovative approach requires a robust Verification and Validation process to secure the credibility assurance of the structural simulation. Simulation overall process is performed in three phases:

1. Material characterization: Definition and verification of the material parameters needed for the CDM application for crack initiation and propagation. Verification of the material models is performed through coupon test simulations to confirm the expected response. This phase is general and linked to the specific material.

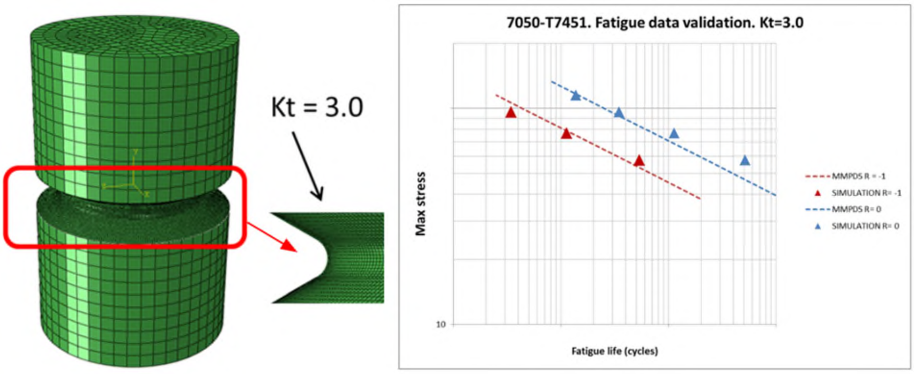

Figure 5: Virtual coupon test to verify the material model versus test results

2. Subcomponent test validation (Validation phase): A representative subcomponent physical test campaign is used to correlate the simulation results to validate the methodology to be used for the predictions in the actual flight conditions, being the test representative of the real design and its load state.

3. Real flight condition prediction (application phase): Simulation of the critical frame location. Crack initiation and propagation results are confirmed against real in-service findings. The modelling criteria and simulation methodology used in this phase is exactly the same as in the Validation phase

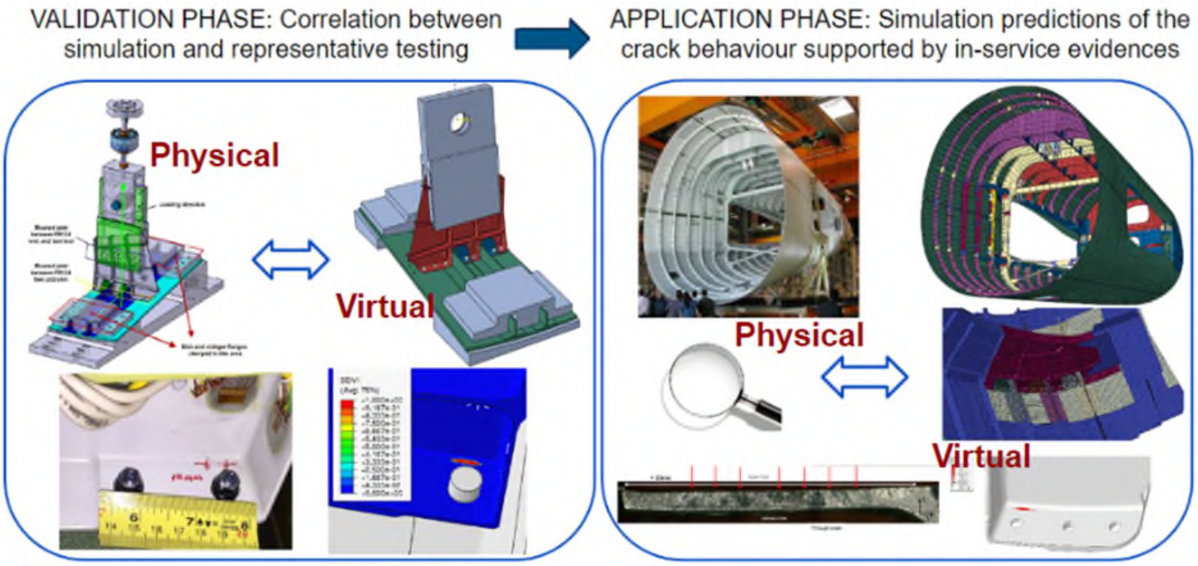

Figure 6: Simulation process of a fuselage frame unfolding

Subcomponent test validation (Validation phase)

Validation of the methodology versus tests provides a simulation credibility framework to sustain the predictions for the fleet with confidence as recognized by Airworthiness authorities (See Ref. 10).

As can be seen in Figure 6, a highly detailed Finite Element Model is used to perform the virtual test simulation. This model is the reference to be used for both residual and crack initiation and propagation tests. The differentiation between the static (intact and residual) and fatigue test rely on the CDM material modelling and the analysis type as explained in the CDM NUMERICAL IMPLEMENTATION chapter.

1) Intact and residual Strength Subcomponent test correlation

Correlation with CDM models is done for both the intact and a cracked specimen for residual strength. Intact static test and residual strength test simulations are performed with the same baseline model, but for residual strength, initial crack is introduced according to the real crack findings in the test after cycling.

It should be highlighted that in the physical residual strength tests, the same strength capability was observed for the specimen in intact conditions or with damages, sustaining for the different residual strength specimens a maximum test load with less than 5% difference than intact specimen.

The virtual test simulations correlation was performed for strain gauges measurements, evolution and maximum test load and specimen damage. Figure 7 shows the comparison in the load vs. displacement evolution perfectly capturing the maximum test load. Figure 8 compares the final status of the critical frame foot for the specimen, where it can be observed that simulations capture not only the critical area but also the damage initiation and propagation with accuracy.

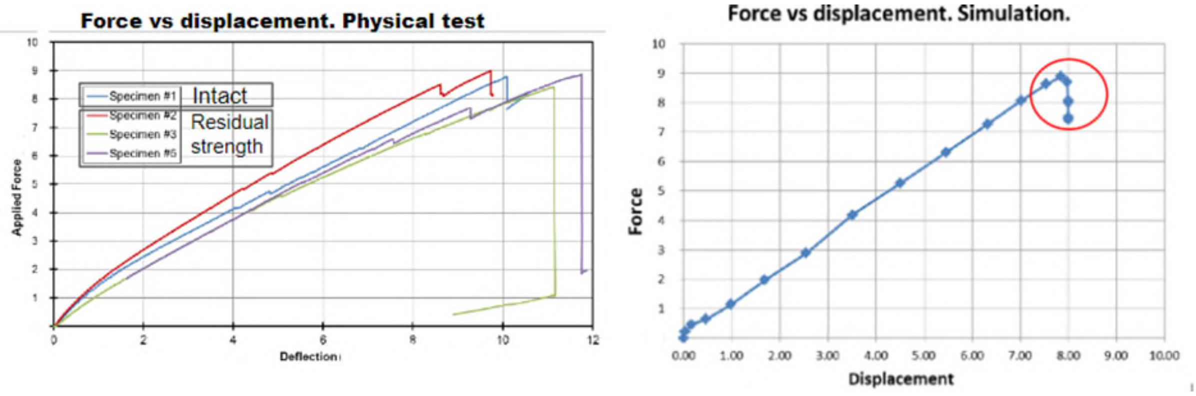

Figure 7: Physical vs. Virtual test load vs. displacement evolution

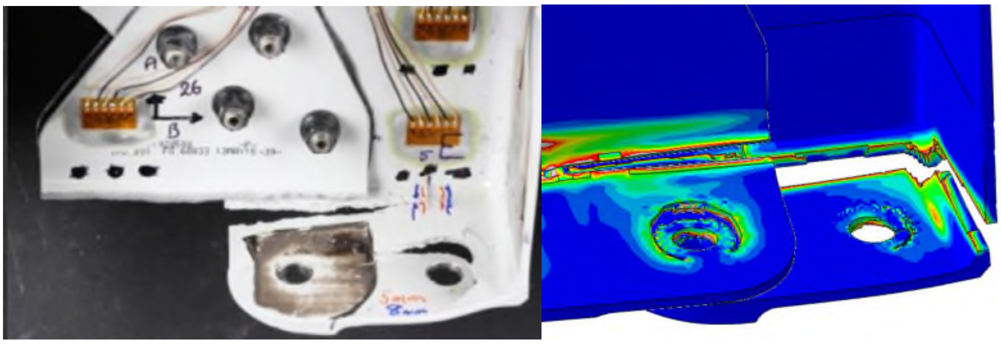

Figure 8: Physical (clip foot partially removed) vs. Virtual specimen status after residual strength test

2) Fatigue Subcomponent test correlation

Fatigue test simulations were correlated versus monotonic spectrum fatigue tests performed. Both the location of the cracks and their initiation and propagation were compared and evaluated. As can be seen in figure 9, the crack locations in the virtual test matched the locations in the physical specimen, and therefore all the critical areas and their qualitative evolution behavior along the test were captured in the simulation. Figure 10 also highlights two states of the crack propagation for different critical cracks, and it is observed that the simulation behaves similarly to the tests with very good correlation considering a reasonable scatter. It is important to highlight that for this specific application, the most critical locations results are slightly conservative in the CDM simulation.

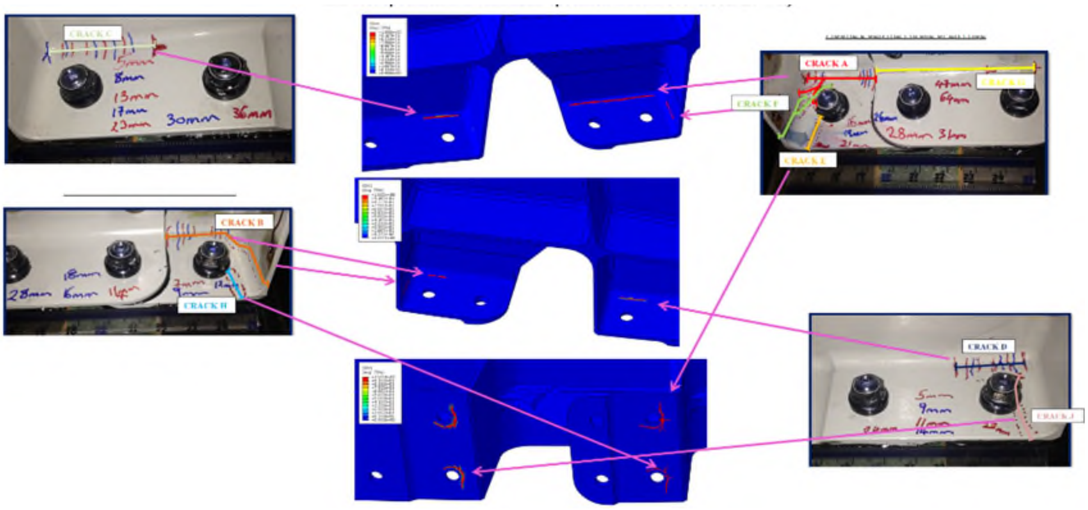

Figure 9: Physical vs. Virtual specimen crack scenario after cycling

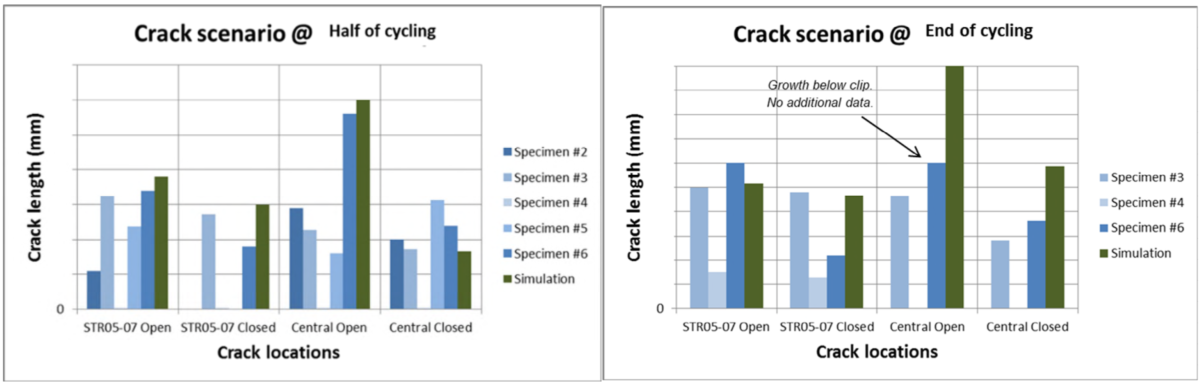

Figure 10: Physical vs. Virtual test crack length for two cycling status

Real flight condition prediction (application phase)

As shown in Figure 4, the simulation from global to local approach has been followed from a complete component Detailed NL-FEM with enough granularity to capture the overall nonlinear effects, providing the proper loading and boundary conditions to the very detailed NL-FEM of the frame feet to be analyzed. Is in such area of analysis, where the CDM modelling requirements are implemented using 3D 2nd-order tetrahedral elements of 0.1mm.

1) Residual strength Simulation

The intention of the application of CDM methodology for flight configuration has been to support the justification of the residual strength capability of the structure with in-service cracking scenarios.
An initial crack has been implemented physically in the mesh for the Residual Strength simulations as shown in figure 11, with the same size, shape and location as it has been detected in service fleet findings.

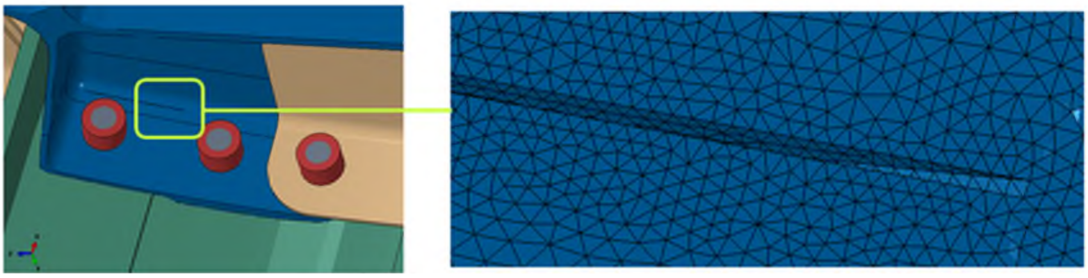

Figure 11: Simulated crack for Residual Strength Simulation

During the simulation, static loads were increased up to UL and maintained with just only a slightly static propagation of the crack. Figure 12 shows the internal strain energy and damage energy evolution (with event description) and the final status of the crack. The surrounding structure was also evaluated to demonstrate there was no failure due to load redistributions in the area.

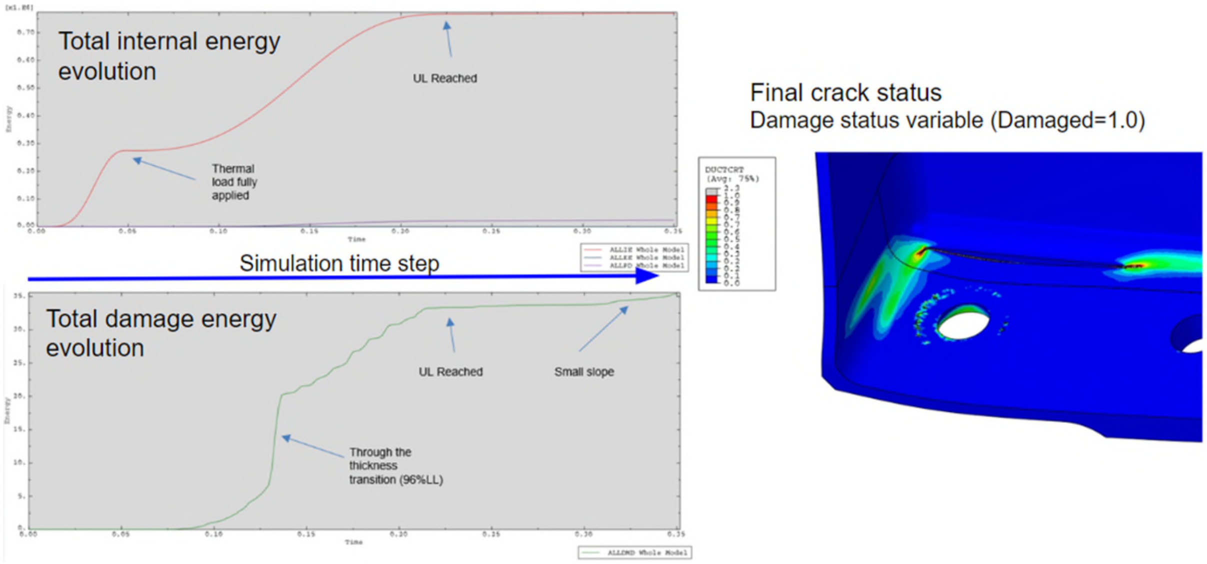

Figure 12: Evolution of the FEM energy with the associated events & final frame foot crack status

Thanks to the above residual strength simulation, it was demonstrated first that the in-service cracking scenario sustains the current certificated static Ultimate loads and second, which will be the critical crack length under Limit and Ultimate load. The critical crack length status at Ultimate Load is shown in figure 13.

Finally, a complete cracked critical foot was also simulated sustaining the current static Ultimate loads, and demonstrating a multiple load path design capability.

In summary, the mentioned simulation demonstrated the safety condition of the fleet as far as residual strength is concerned.

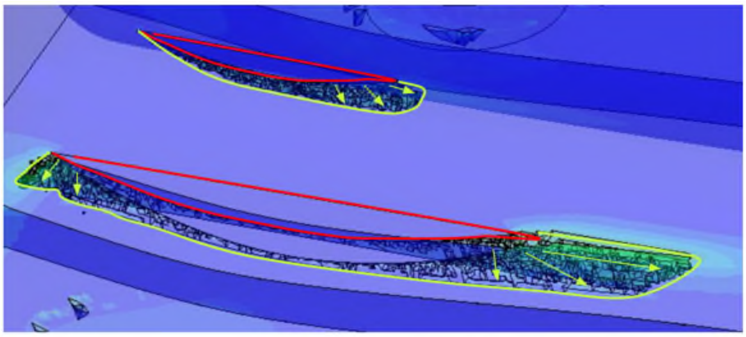

Figure 13: Initial crack implemented s and final crack status in the simulation under static loads

2) Crack initiation and propagation Simulation

An equivalent CDM simulation to the one performed for the subcomponent test during validation phase for crack initiation and propagation was performed in the in-service critical foot frame location.

As the loading spectrum is concerned, the real fatigue stress sequence for the flight configuration will be simplified in accordance with Airbus internal rules to a constant amplitude sequence with a ratio between the peak and the minimum value of 0.1.

Regarding the material properties used for the simulation, crack initiation was predicted in the range of low cycle fatigue with Peerlings material parameters calibrated from material ε-N curve to assure the material response was accurate for the range of application.

In Figure 14, the result summary of the CDM simulation is shown. It can be seen that the crack initiation location, shape and size was matching with the in service fleet findings and subcomponent test evidence.

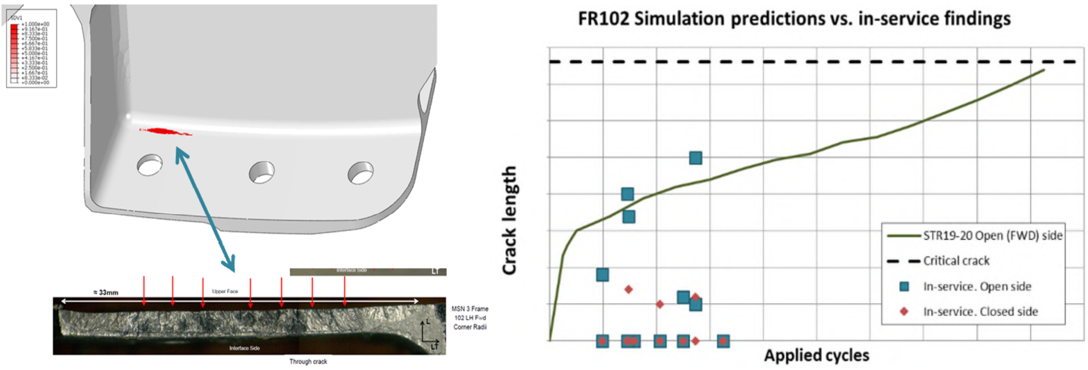

Figure 14: Crack initiation location and propagation predicted by the Simulation vs in service experience

The main fracture mechanism of the studied cracks: multiple superficial voids and sudden coalescence to a relatively superficial long crack, followed by a slow superficial propagation for a non-through thickness crack, as observed in the in-service and test findings, was highly predicted by the CDM simulation.

These results of the overall CDM simulations have been used to support the time to react for the mandatory inspections and repairs of the in-service flying fleet.

APPLICATION #2: CRACK FINDING IN HTP UPPER SKIN

From GFEM to DFEM: Main CDM Simulation Parameters

The computational effort needed for the simulation is high, so the starting point is the local area from a more global FEM of the structural part where we are interested in running the CDM simulation. In this local area, a specific finite element model refining process is performed using Abaqus software, to assure that the mesh and material properties are the proper one, considering the level of detail needed to simulate the initiation and propagation phase. For example, the minimum mesh size element in the area considered in the simulation is 0.5mm.

On Figure 15, the finite element model used is shown, including the design detail refined to run the CDM simulation inside of the green square in the mentioned Abaqus DFEM.

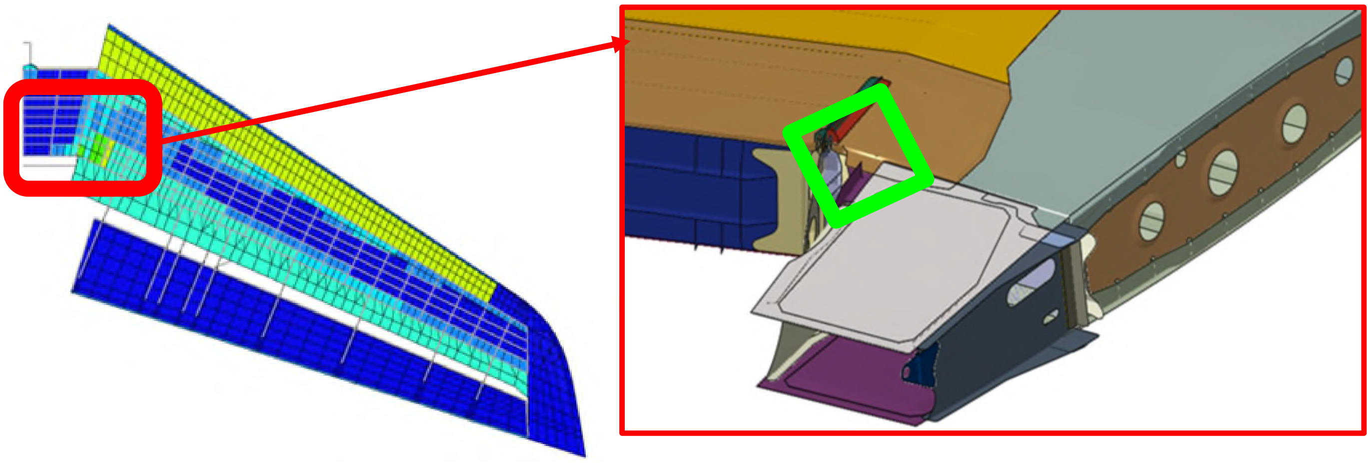

Figure 15: GFEM and DFEM employed in the simulation

The key main parameters of this CDM simulation are the loading spectrum sequence applied to the DFEM and specially the material properties of the structure part. As the loading spectrum is concerned, in this case, the real fatigue stress sequence will be simplified in accordance with Airbus internal rules to a constant amplitude sequence with a ratio between the peak and the minimum value of 0.1.

Regarding the material properties of the local structure to be considered for the CDM simulation, as explained in the introduction, will be calibrated on purpose to be used with the damage model selected in this paper, i.e. Peerlings model from [6]. Such calibration of the material properties is done for the specific alloy versus the current test material data and it considers any contribution to the behavior of the initiation and crack propagation of the material, such surface treatment or any scale factor correction considered for the material test data. In Figure 16, the result of this calibration is shown against the test data for the aluminum alloy of the part where the simulation will be run.

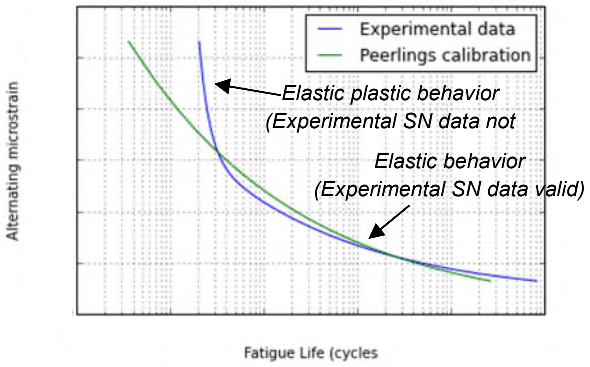

Figure 16: Material Properties calibration for the simulation

Full Scale Test CDM Simulation: Damage Initiation and Propagation Validation and Verification

As part of the standard validation and verification process applied to this type of detailed simulation, which Airbus considers is fundamental to control the level of uncertainties, the CDM simulation presented in the previous chapter will be first applied against the current structure test data available in the area, in this case, against the result of the full scale test of the Horizontal tail plane performed in the frame of the type certification process. In this context, the first step is to simulate with the Abaqus DFEM, the mentioned tested configuration, thanks to the strain gauges used during the test for global stress distribution. As an example, some of the strain gauges in the area of interest and the global strain gauge correlation versus the test.

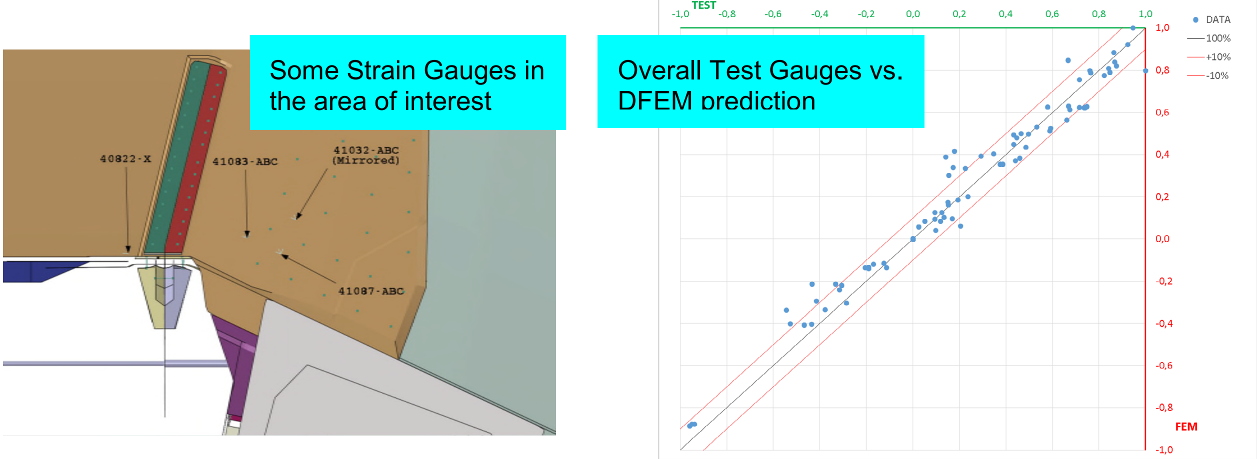

Figure 17: DFEM Strain gauge correlation vs test

Second step, once the FEA shows good correlation versus the full-scale test in the area of interest, the CDM simulation is launched considering the main loading and material parameters described in the previous subchapter. Main conclusion is that the crack initiation point and subsequent propagation are in line with the test result and with the results from the laboratory investigation, despite that the available test data was for very small crack lengths.

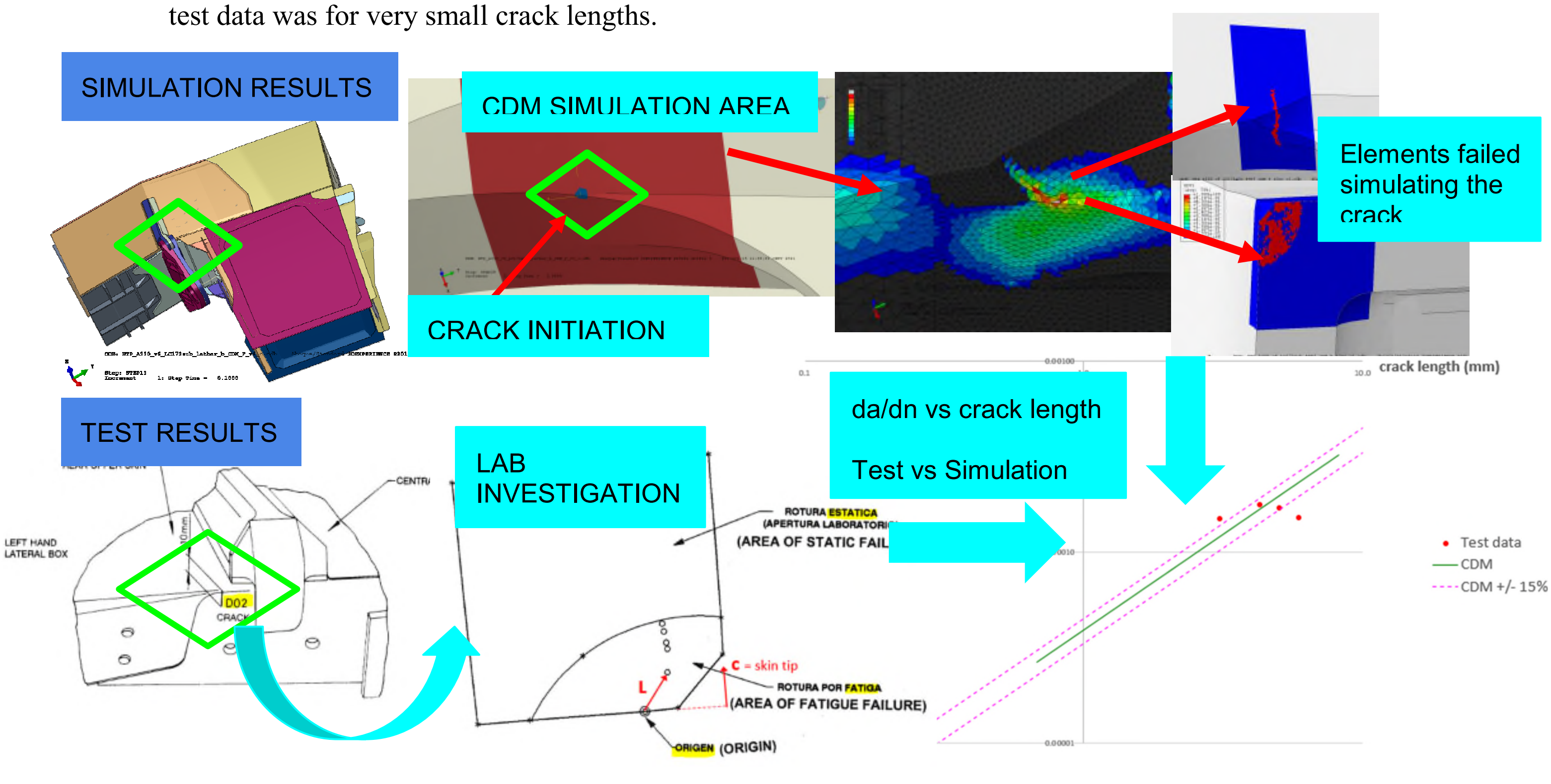

Figure 18: Test & Simulation results comparison

Application to Real Flight Configuration: CDM Simulation vs. Theoretical Analysis

Once the validation and verification process of the Abaqus DFEM representing the tested HTP configuration, is found to be acceptable, it will be employed to support a CDM simulation of similar configuration submitted to a different load state, in this case, the so called in flight configuration in the present paper. The objective is first to compare the result of the explained CDM simulation on the previous chapter against the classical analytical prediction method and in a second step, under certain circumstances to use the result of this last simulation to define the in-service aircraft frequency to inspect the area as part of the scheduled maintenance program.

The result of the simulation has been proven highly comparable to the test experience in the area explained in the previous chapter. Next Figure 19 shows the first initiation of the crack and the subsequent crack propagation of the crack predicted by the CDM simulation. Shall to say that this prediction was fully aligned also with the in service-cracking scenario detected.

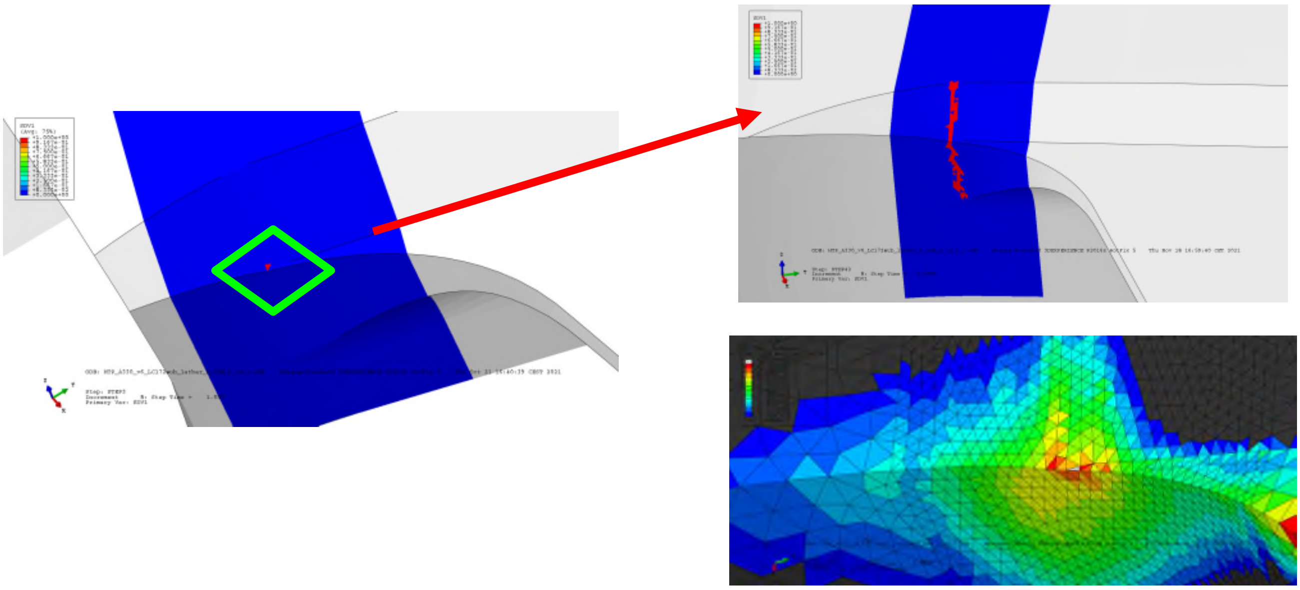

Figure 19: Crack Initiation and propagation from the CDM simulation

Finally the comparison between the theoretical crack growth curve obtained with classical methodology and the CDM simulation result is shown below in Figure 20, where it can be seen a lower crack growth rate predicted thanks to the CDM simulation.

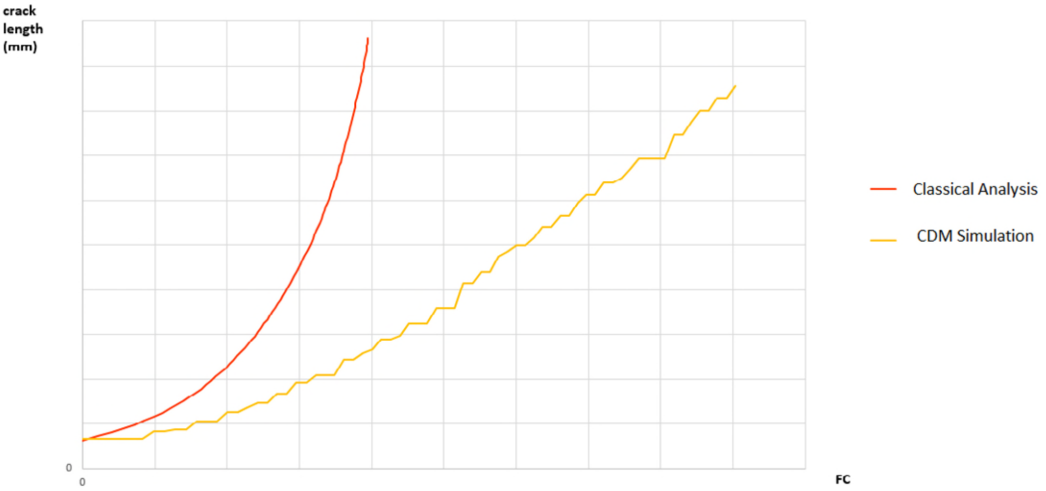

Figure 20: Crack Length Propagation Curve based on Analysis vs CDM simulation

CONCLUSIONS AND WAY FORWARD

The simulations presented in this paper, used to first correlate the test experience behind and validate the approach and the later application to the two real cases presented, are based on Continuum Damage Mechanics with ductile damage model for strength prediction and a fatigue damage model based on alternating strains for fatigue cracking prediction.

These two applications presented in the current paper are examples of different structure details, submitted to very different load states, where the CDM simulation has proven its flexibility to predict the crack initiation, propagation and failure of the real scenarios that occurred in the corresponding subcomponent or full-scale test.

Application of the methodology in a complex F&DT scenario as it is the unfolding superficial cracks, demonstrated a very good correlation for both residual and fatigue CDM approaches versus subcomponent test and in-service findings. The CDM predictions supported the fleet safety assessment and the optimized inspection plan further than the more conservative conventional methodology originally justified.

Regarding the application on the upper skin of the horizontal tail plane, very good correlation has been obtained for the prediction of the cracking scenario seen in the full scale test with the CDM simulation, despite the highly dependency of the material calibration and local geometry detail as expected.

On both applications, when extrapolating the CDM simulation procedure and technique to the physical configuration of the flying aircraft, non-negligible margins have been increased compared to the more limited classical methods of analysis.

In particular, an increase of 3 times on the prediction of loading cycles up to the crack initiation and +40% to +50% residual strength increase shown in the case of the frame application. For the Horizontal tail plane, the prediction of the crack propagation rate has been improved by a factor of 2.

CDM simulation technique and its application to real in service cracking scenarios has been presented in this paper. One of the key aspects of the overall procedure followed has been to run a full validation and verification process against in house test experience prior to any extrapolation of the simulation to a similar/physical in service configuration. Such validation and verification includes not only coupons or subcomponent tests but also full-scale test experience at the highest level of the test pyramid.

Airbus is committed to continue developing the CDM simulation capabilities, by means of exploring other damage models, with less limitation on triaxiality effects always exploiting the in house extensive test for the best validation and verification processes as possible, since should be the basis for subsequent extensive extrapolation of the simulations.

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REFERENCES

[1] Gómez-Escalonilla, J., Garijo, D., Valencia, O., Rivero, I. (2019). "Development of efficient high-fidelity solutions for virtual fatigue testing". *30th ICAF Symposium.*

[2] Rivero, Ismael, et al. (2022) "Towards Virtual Fatigue Testing: Developments and Challenges for Metallic and Composites Aerostructures." *33rd Congress of the International Council of the Aeronautical Sciences.*

[3] Rivero, I., Palomar, P., Lozano, M., Gómez-Escalonilla, J., Armijo, J. (2019). "Evaluation of the effect of unconventional material cracking over structural residual strength". *NAFEMS World Congress 2019.*

[4] Lemaitre, J., Chaboche ,.J.L., (1990). "Mechanics of Solids Materials". *Cambridge University Press. ISBN 978-0-521-32853.*

[5] Silitonga, S., Malljaars,.J., Soetens, F., Snijder, H.H. (2013). "Survey on damage mechanics models for fatigue life prediction". *Heron 58(1):25-60*

[6] Peerlings, R. (1999). "Enhanced damage modelling for fracture and fatigue". *Proefschrift Technische Universiteit Eindhoven.*

[7] Hooputra, H.; Gese, H.; Dell, H.; Werner, H. (2004). A comprehensive failure model for crashworthiness simulation of aluminium extrusions. *International Journal of Crashworthiness, 9:5, 449-464.*

[8] Bao, Y.; Wierzbicki, T. (2004). On fracture locus in the equivalent strain and stress triaxiality space. *International Journal of Mechanical Sciences 46 81-98.*

[9] Metallic Materials Properties Development and Standardization (MMPDS) Handbook – 11(2016). B-983. *Battelle Memorial Institute.*

[10] EASA CM-S-014 Issue 01. *Certification Memorandum Proposal. Modelling & Simulation – CS-25 Structural Certification Specifications. Draft Version.*

[11] EASA.*Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes CS-25.*

[12] DS Simulia (2016). Abaqus Analysis User's Guide.

[13] DS Simulia (2016). Abaqus User Subroutines Reference Guide.